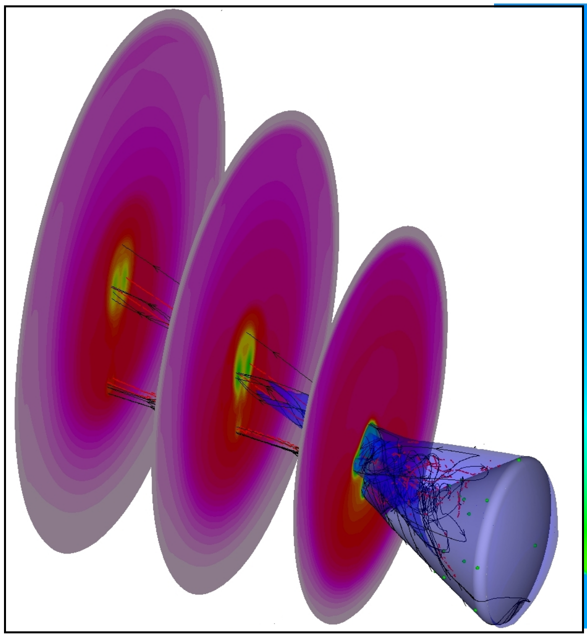
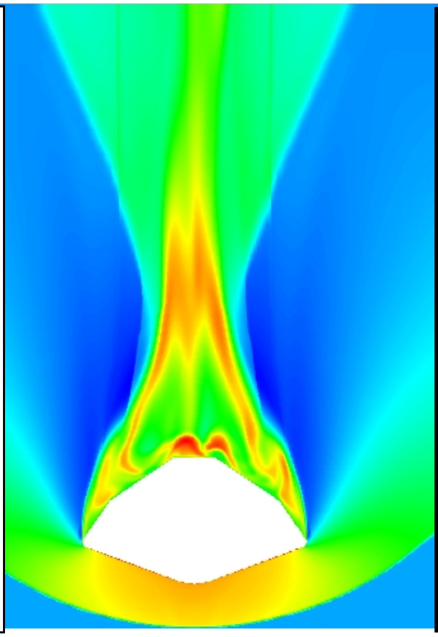
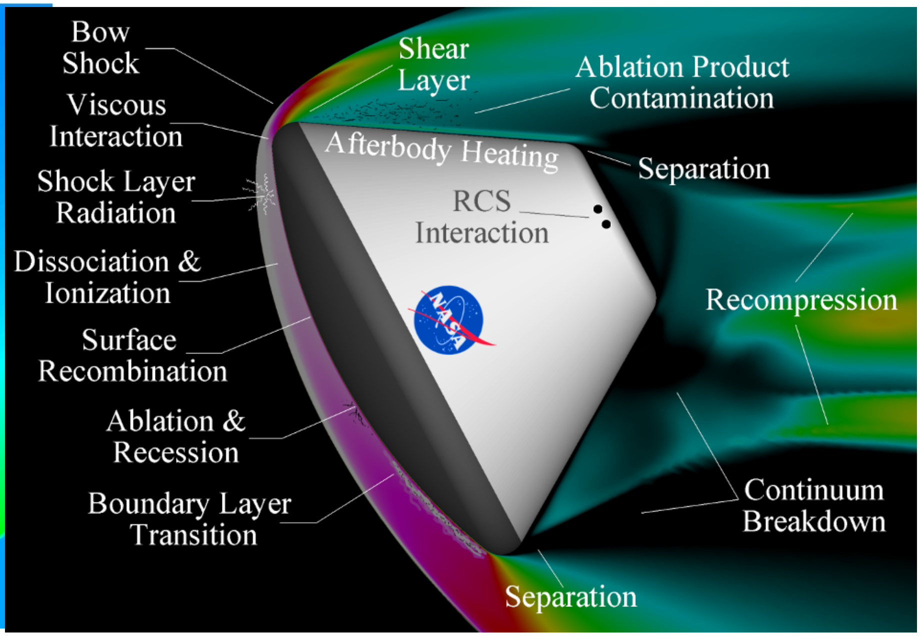
Aerothermal Modeling And Validation







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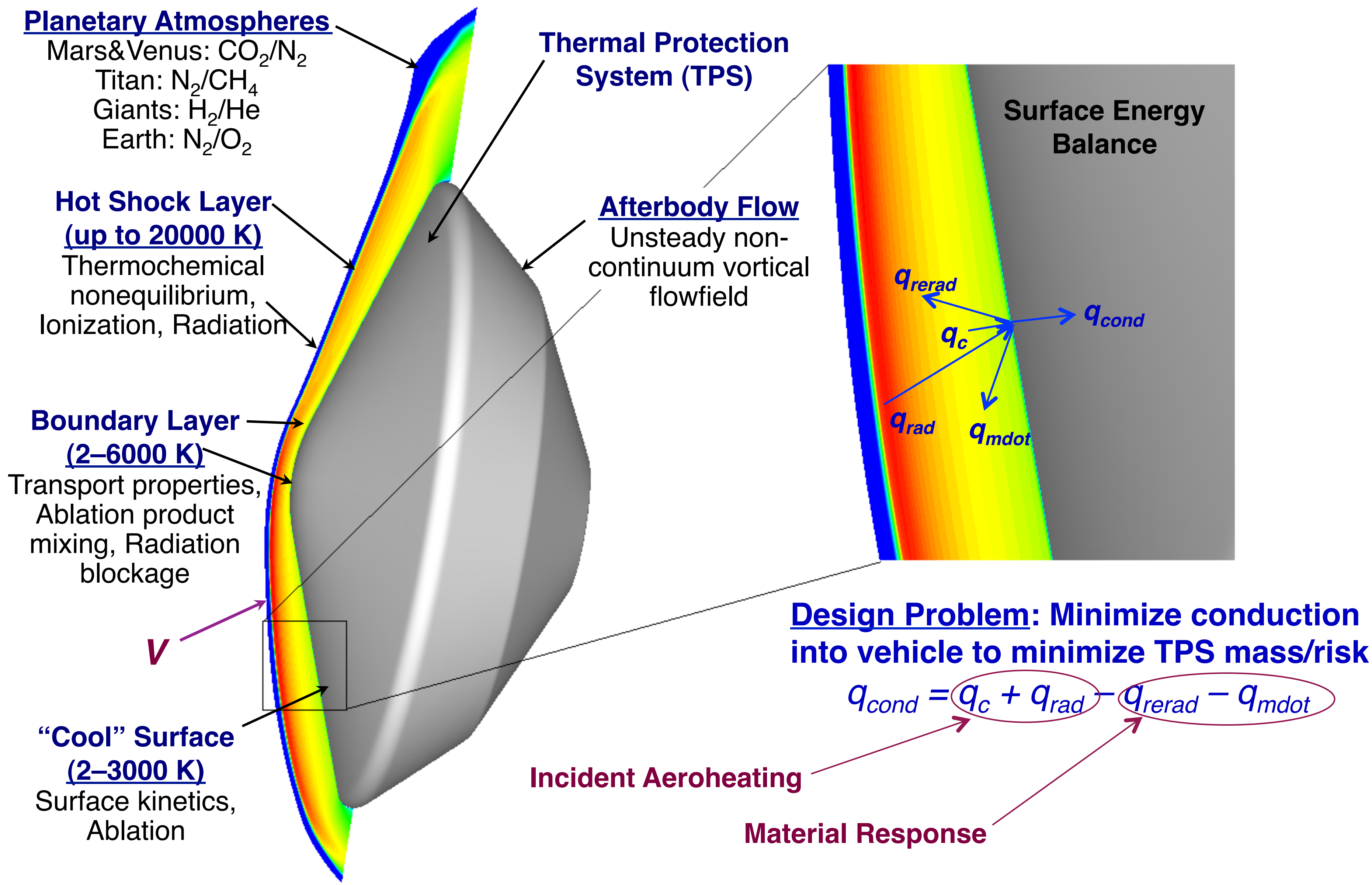
Outline

- What is Aerothermodynamics?
- Current Gaps/Areas for Improvement
- Model Validation

Principles of Aerothermal Models



Why is Aerothermal Modeling Important?

- **Heat flux (with pressure & shear) used to select TPS material**
- **Heat load determines TPS thickness**

Can’t we just ‘cover up’ uncertainties in aerothermal modeling with increased TPS margins?

- **Sometimes, <u>but</u>:**
  - Margin increases mass; ripple effect throughout system
  - Without a good understanding of the environment risk cannot be *quantified*; benefits of TPS margin cannot be traded with other risk reduction strategies
  - Margin cannot retire risk of exceeding performance limits
  - For some missions (i.e. Neptune aerocapture, Jupiter polar probe), improved aerothermal models may be *enabling*

Can’t we retire all uncertainties via testing?

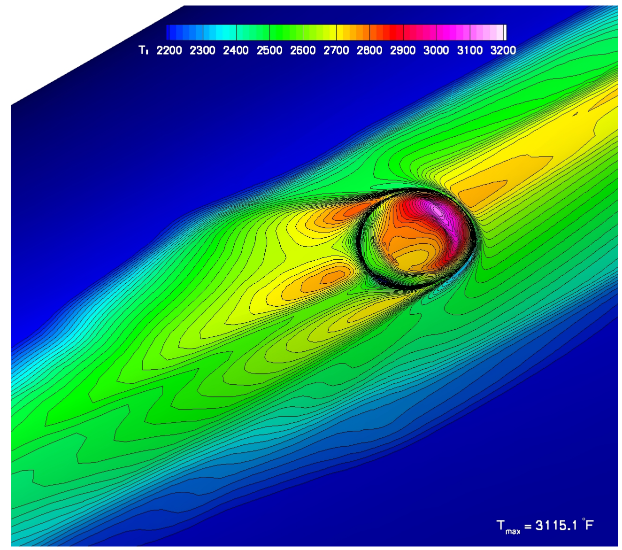
- **No!:**
  - No ground test can simultaneously reproduce all aspects of the flight environment. A good understanding of the underlying physics is *required* to trace ground test results to flight.
  - Flight testing should be reserved for model and system validation, after we have good physics-based models of the expected environment

- Missions and Problems of Interest
- What is Aerothermodynamics?
- **Current Gaps/Areas for Improvement**
- Model Validation

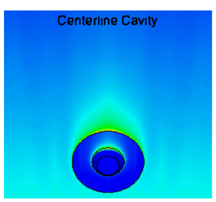
CFD Process for Entry Vehicle Design

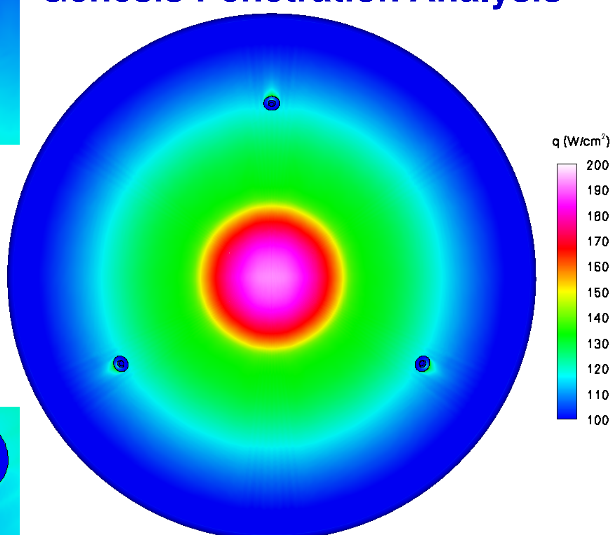
- **High fidelity CFD tools based on 20-year old methodologies**
- **Recent advances in parallel computing, efficient implicit algorithms have enabled rapid turnaround capability for complex geometries**
- **Full body three-dimensional CFD is an integral part of the design of all planetary and Earth entry TPS**

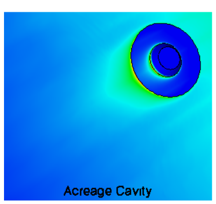
Shuttle RCC Repair Concept Evaluation



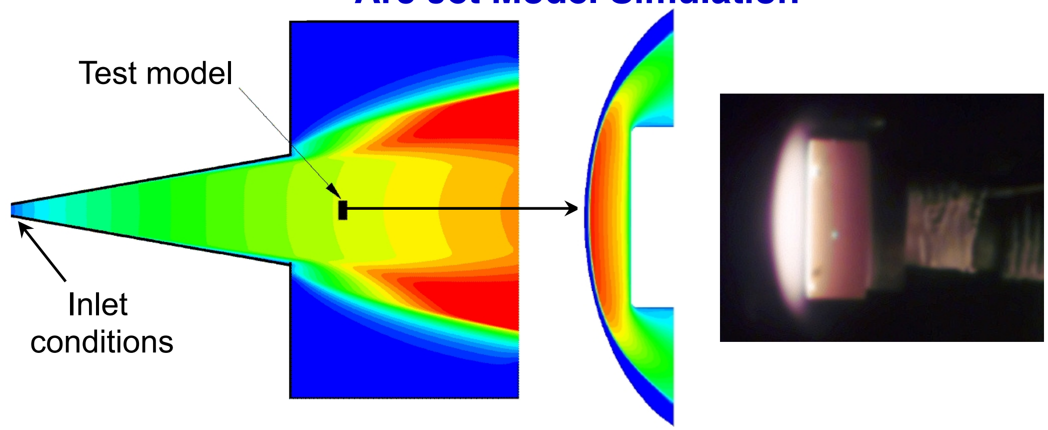
Genesis Penetration Analysis







Arc Jet Model Simulation



Nozzle flow CFD simulation **Model CFD simulation** **Arc jet test**

Identification of Aerothermal Modeling Needs for Entry Missions

- **Needs are both physics and process driven**
  - process improvements are important for modeling complex geometries - not covered in this presentation
  - physical model improvements are important across the spectrum of NASA missions
- **Gaps are destination <u>and</u> mission specific**
  - shock layer radiation in particular will dominate aeroheating for some missions and be unimportant for others
  - sensitivity analysis must be performed for each candidate mission
- **Gaps can be divided into general categories**
  - surface kinetics
  - transition and turbulence
  - shock layer radiation modeling
  - afterbody heating
  - coupling between radiation/material response/fluid dynamics/aerodynamics
  - reacting gas physical models
  - unsteady separated flows (wakes, control surface shock-BL interaction)
  - geometry effects

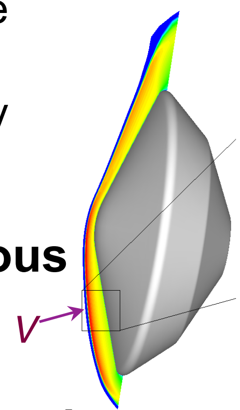
Consumer Reports

	Earth			Venus	Mars		Titan	G.P.	Jupiter
	LEO	Samples	Lunar+		Robotic	Human			
Laminar									N/A
Transition		N/A		N/A					N/A
Turbulence									
Roughness									
Surface Chemistry									
Radiation	N/A				(N/A)				
Afterbody									
Coupling	N/A	N/A			N/A				
Reacting Gas Mod.									

- Models well validated
- Models partially validated
- Models largely unvalidated
- Some models do not exist
- No credible model exists

Surface Kinetics

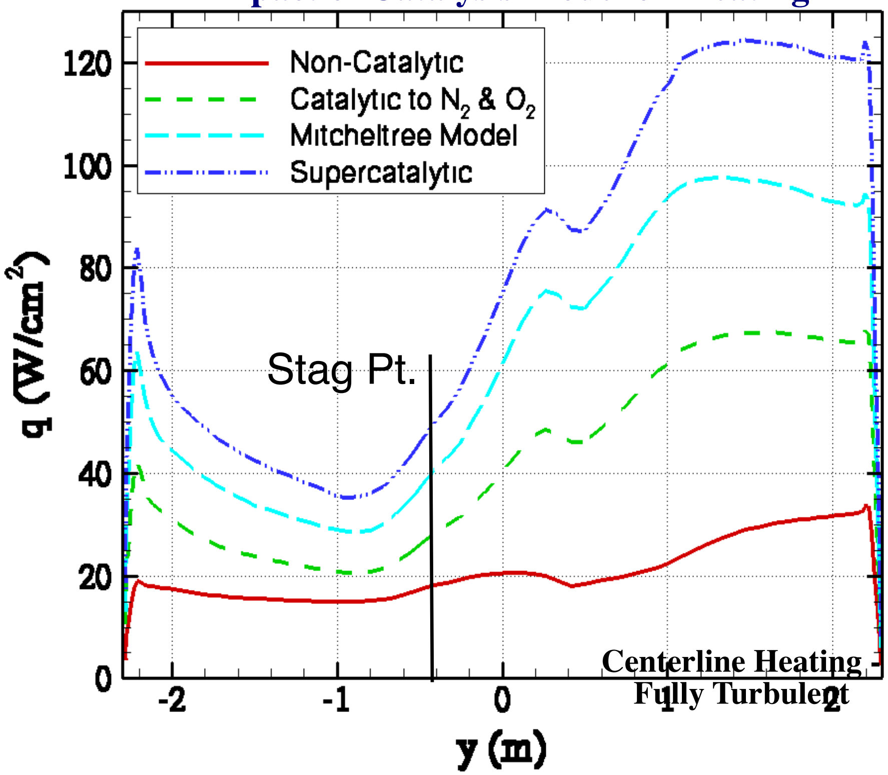
- **Catalysis: surface facilitates recombination of incident species**
  - increases heat transfer to surface
  - material/coating specific
  - models exist for Earth; low fidelity for Mars/planetary applications



- **Homogenous and heterogeneous processes can occur. Actual mechanism is a complicated multi-step process (adsorption, site hopping, bond breaking and formation, desorption)**

- **Ablating surfaces also react with the boundary layer via oxidation, sublimation and other <u>participatory</u> processes.**

Mars Science Laboratory - Impact of Catalysis Model on Heating



- **Problem area:**
  - Validated models for flight-relevant surface chemistry do not exist. This is an active area of research in the community

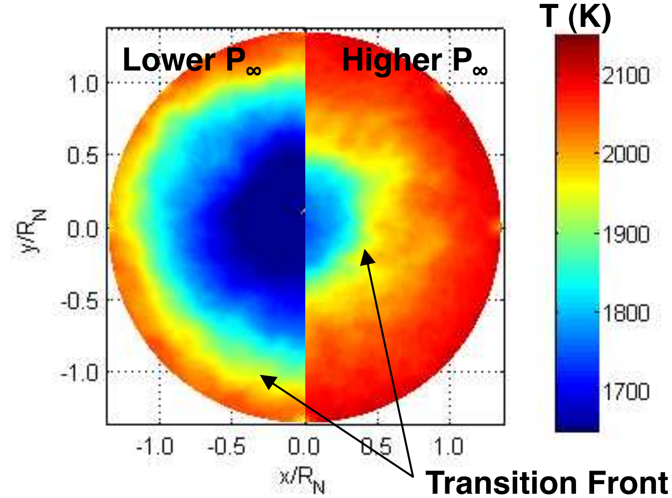
Transition and Turbulence

Status and Remaining Gaps

- **Transition is less of a concern for blunt capsules**
  - shorter trajectories, smaller surface area leads to less heat load augmentation
  - single use ablative TPS can withstand heating if mass penalty not large – design to fully turbulent
- **Acreage turbulent heating predictions generally within 25% for orbital Earth entries (RANS)**
- **RANS models are being employed far outside their comfort zone for most problems**
  - Hypersonic shocks, nonequilibrium chemistry, shock layer radiation, non-Earth gas mixtures
- **Problem areas:**
  - Will we ever have a truly predictive capability for transition?
  - Can any RANS model accurately predict separated wake (base) flows?
  - Will LES/DES become extensible to this regime and become useful for design?
  - Can DNS be used to develop subgrid scale models for RANS/LES?

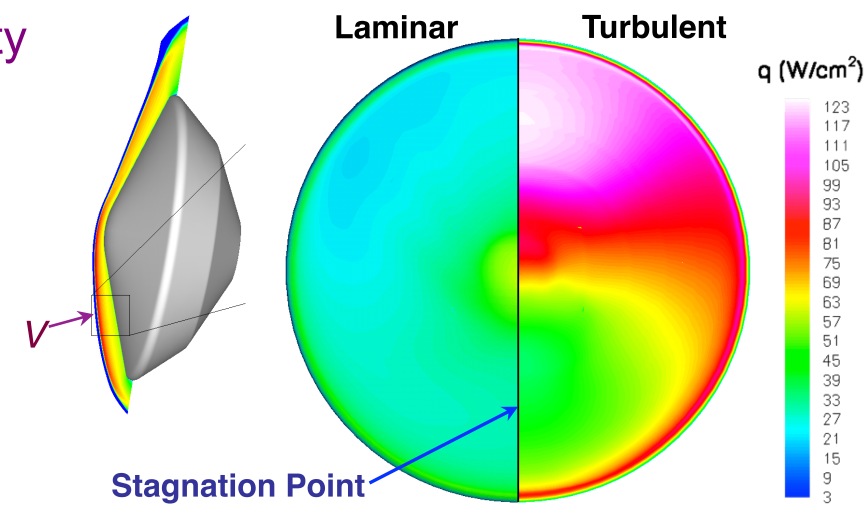
70º Sphere-Cone:

Hypersonic Flight in Ballistic Range



Mars Science Laboratory

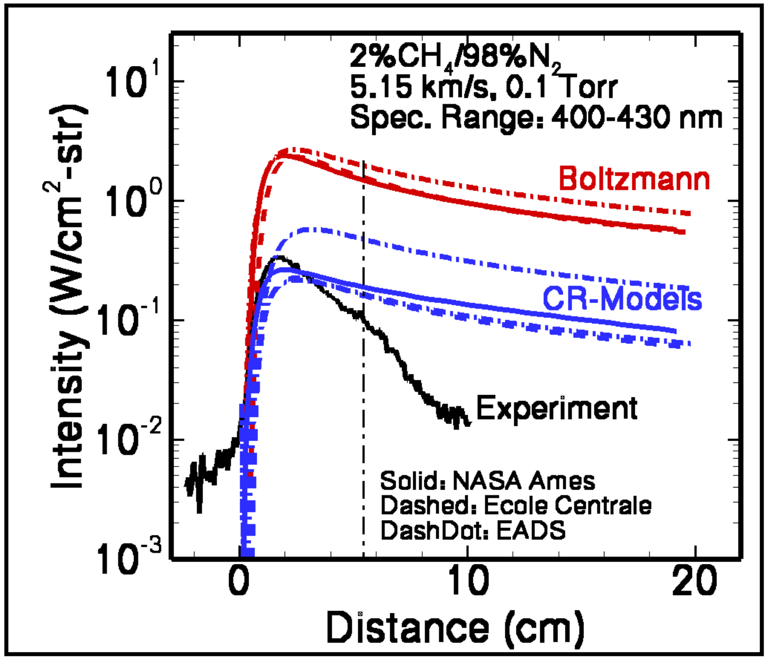
Peak Heating Condition



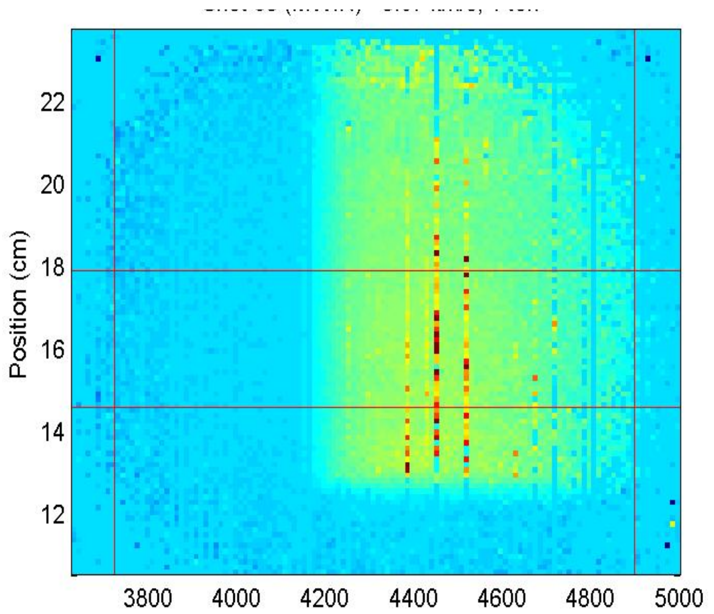
Shock Layer Radiation

- **Shock layer radiation is highly non-equilibrium, non-blackbody**
  - Titan analysis showed order of magnitude differences between equilibrium & accurate model
- **Not important for Mars missions to date, but critical for the future**
  - importance increases with velocity & vehicle size
  - primary radiator, CO(4+) emits in UV & Mid IR

CN Radiation Model Validation



Mid IR Radiation in CO2



from Bose, ARC

- **What are the key gaps?**
  - Importance of CO_2 mid-IR?
  - obtain additional shock tube data
  - build collisional-radiative models for all atomic and molecular radiators
  - compute excitation rates from QM
  - develop medium-fidelity methods for design
  - develop models for coupling to fluids

- What is Aerothermodynamics?
- Current Gaps/Areas for Improvement
- **Model Validation**

What Does it Mean?

- *Verification*: Are we solving the equations right?
  - Is the code employed accurate and correct
  - Is the solution obtained accurate and correct

- *Validation*: Are we solving the right equations?
  - Comparison of computational solution with experimental data

Ref: *AIAA Journal,* Vol 41, No. 10

Validating Aerothermal Models

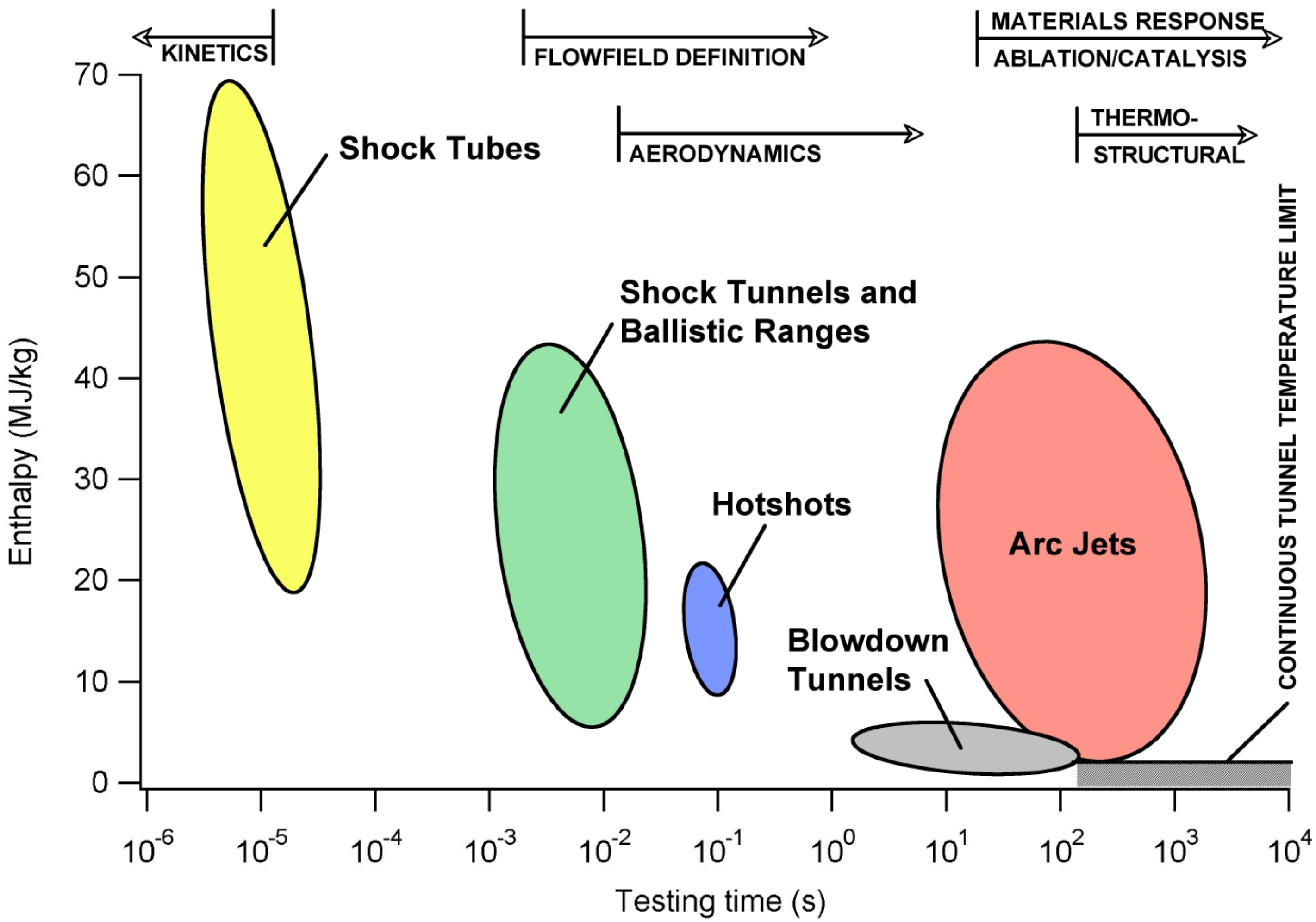
- **Fact #1: There is no ground facility that can replicate all aspects of reentry environment**
  - Every ground test is a compromise. Matching 2 or maybe 3 flight parameters simultaneously is possible only if the others are "released"
  - Creates a challenge; how do we design meaningful tests without overtesting in one of the "released" variables, and without leaving large areas of "n-vector" space untested?

- **Fact #2: Dedicated flight testing is too expensive to be a commonplace part of aerothermal model validation**

- **Fact #3: Because of Facts #1 & #2, aerothermal models must be used to extrapolate ground test results to the flight environment**
  - Places greater emphasis on the development of high-fidelity models and thorough component validation on the ground

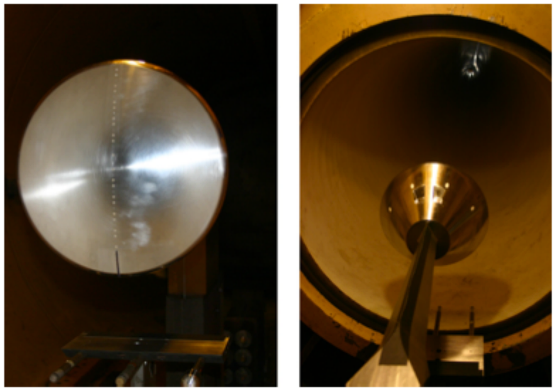
Because of this, flight data are CRITICAL to the model validation and improvement process. In lieu of dedicated flight tests, it is necessary that we include EDL instrumentation on all of our science missions

Ground Test Facilities

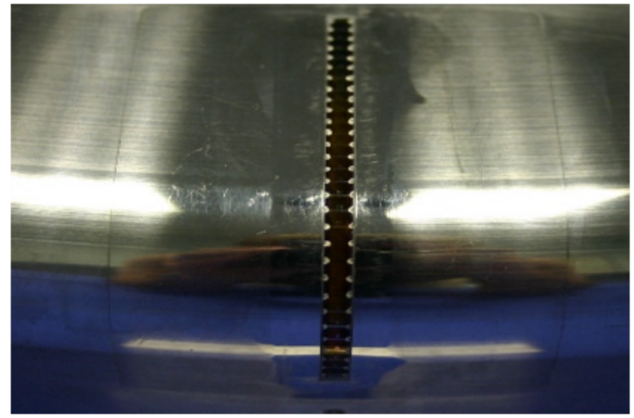


- **Picking the right facility for validation can be difficult…**

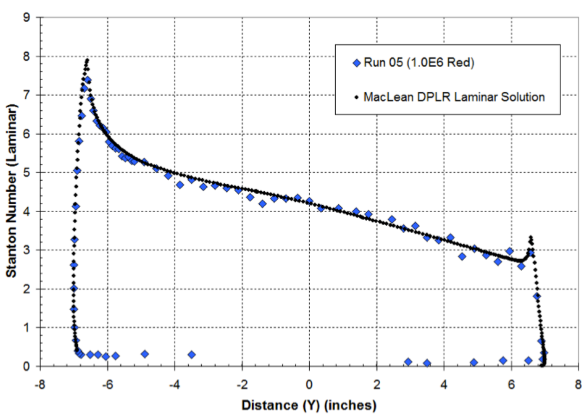
Acreage Heat Transfer



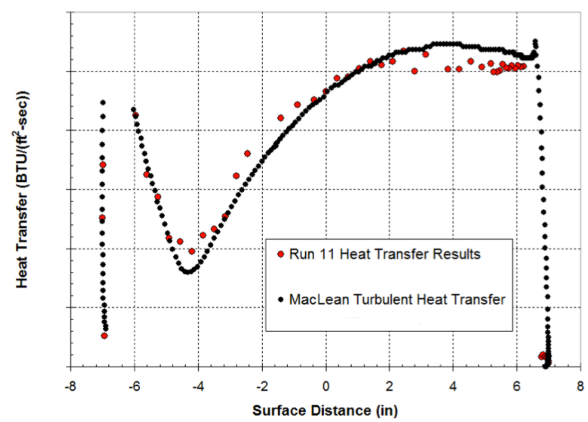
14” Diameter Spherical Capsule Model Installed in LENS-I



Dense Heat Transfer Instrumentation Installed on Windward Shoulder



Data and Laminar Prediction using DPLR Code

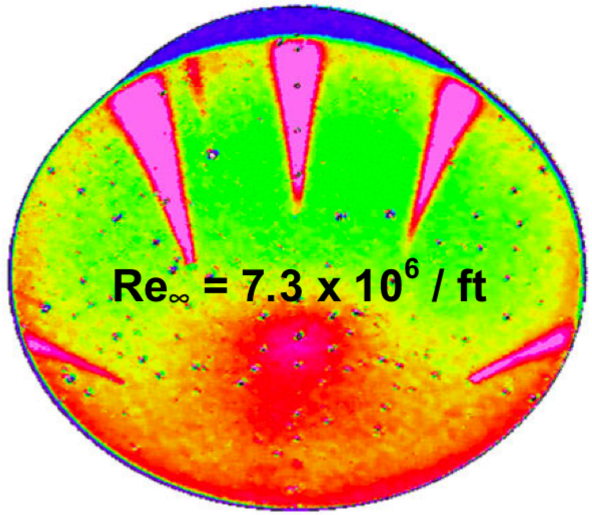


Data and Turbulent Prediction using DPLR Code

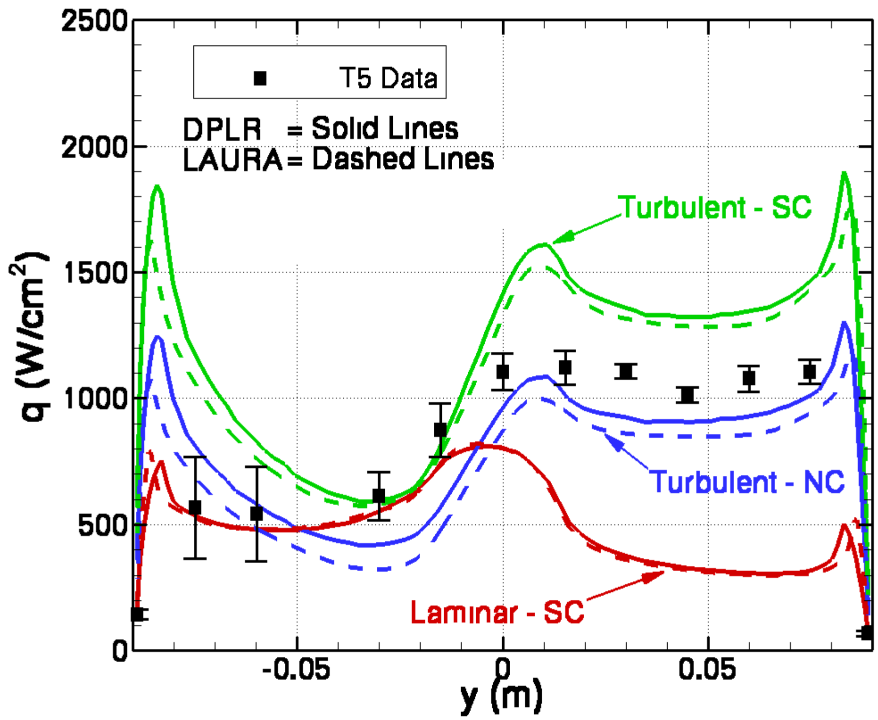
MSL Leeside Heating

- Sometimes the validation step leads to new understanding of the physics…
- For MSL, turbulent testing in the LaRC Mach 6 tunnel revealed (at that time) unexpectedly high leeside heating rates

Mach 6 Tripped



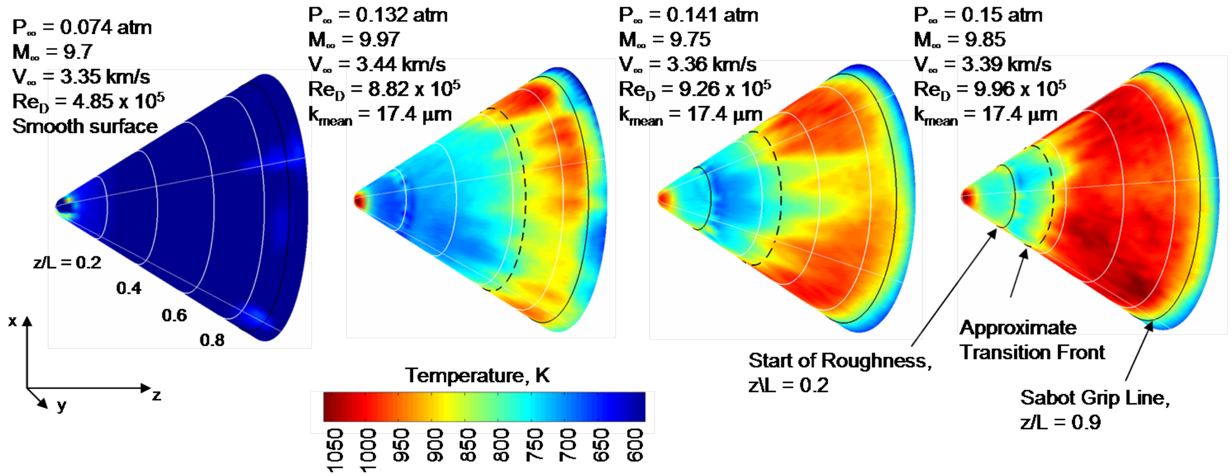
T5 Natural Transition



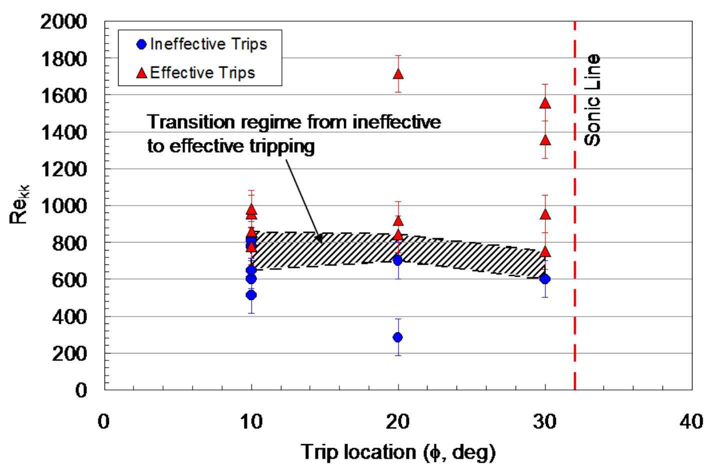
- The phenomenon was later reproduced in a range of facilities including wind tunnels and shock tunnels, and is now understood to be due to entropy swallowing (and actually fairly well predicted with RANS models)

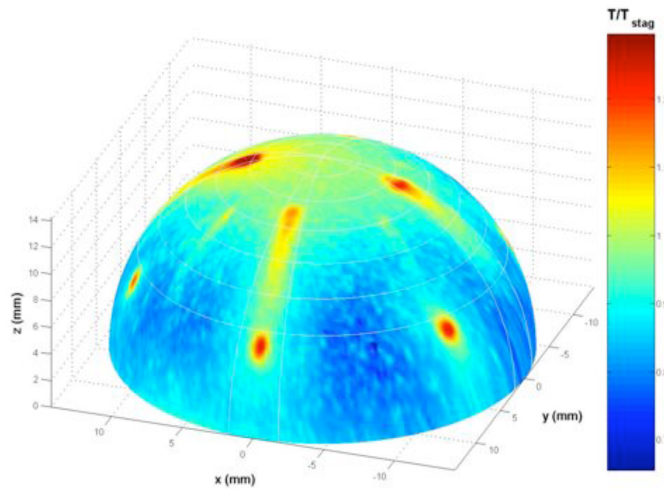
Transition Measurements in Ballistic Range

- Transition measurements due to distributed roughness in flight like enthalpy



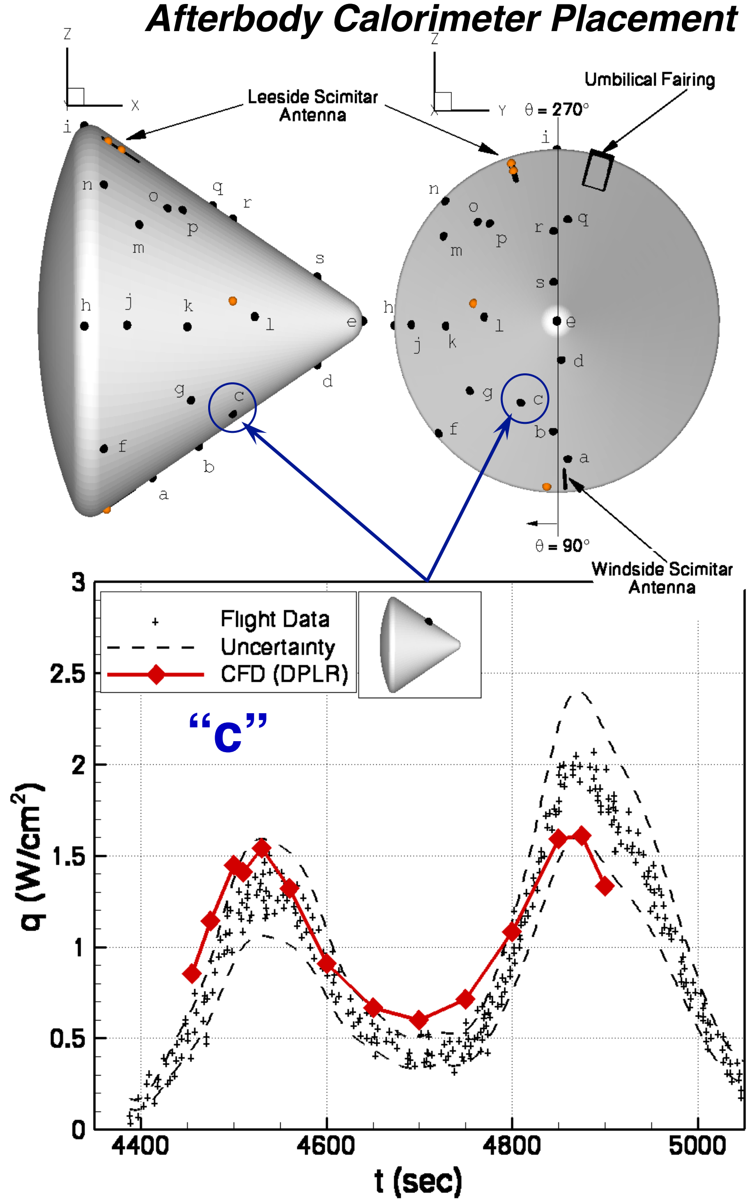
- Transition measurements and correlation development in CO_2 environment for isolated roughness



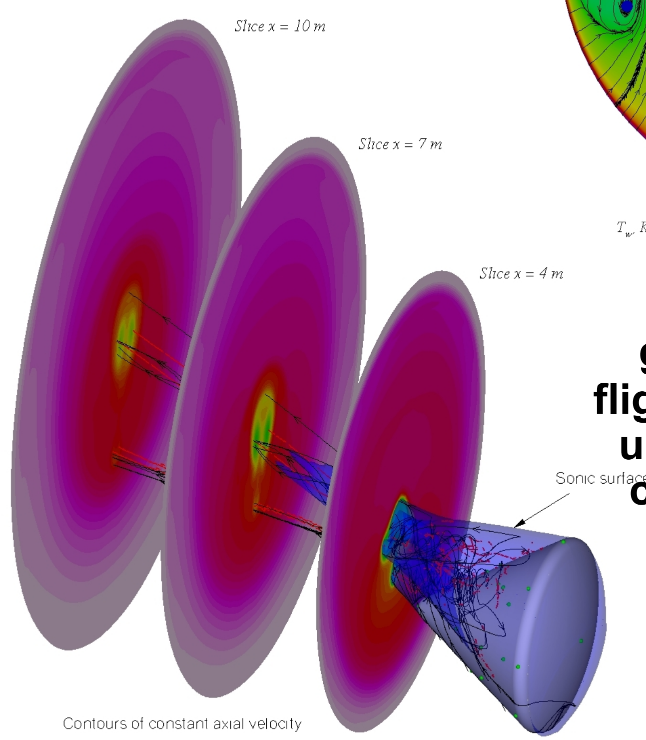


Validation:
AS-202 Flight Data

Afterbody Calorimeter Placement

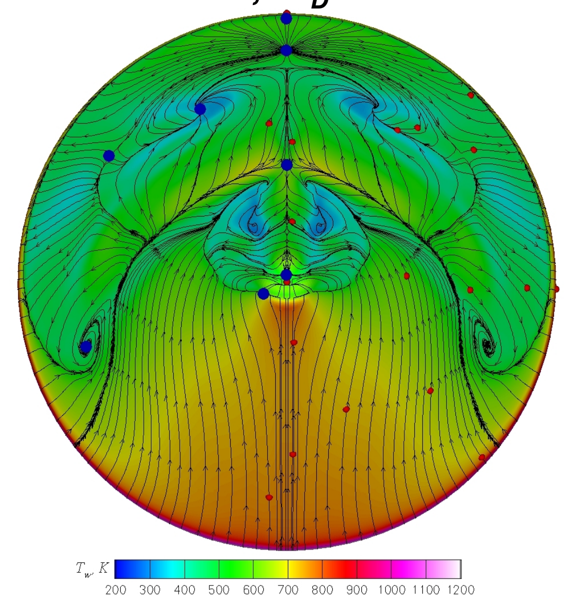


- **<u>Problem</u>:** Current uncertainty on afterbody heating predictions is very high
- **<u>Goal</u>:** reduce uncertainty levels by validation with flight data



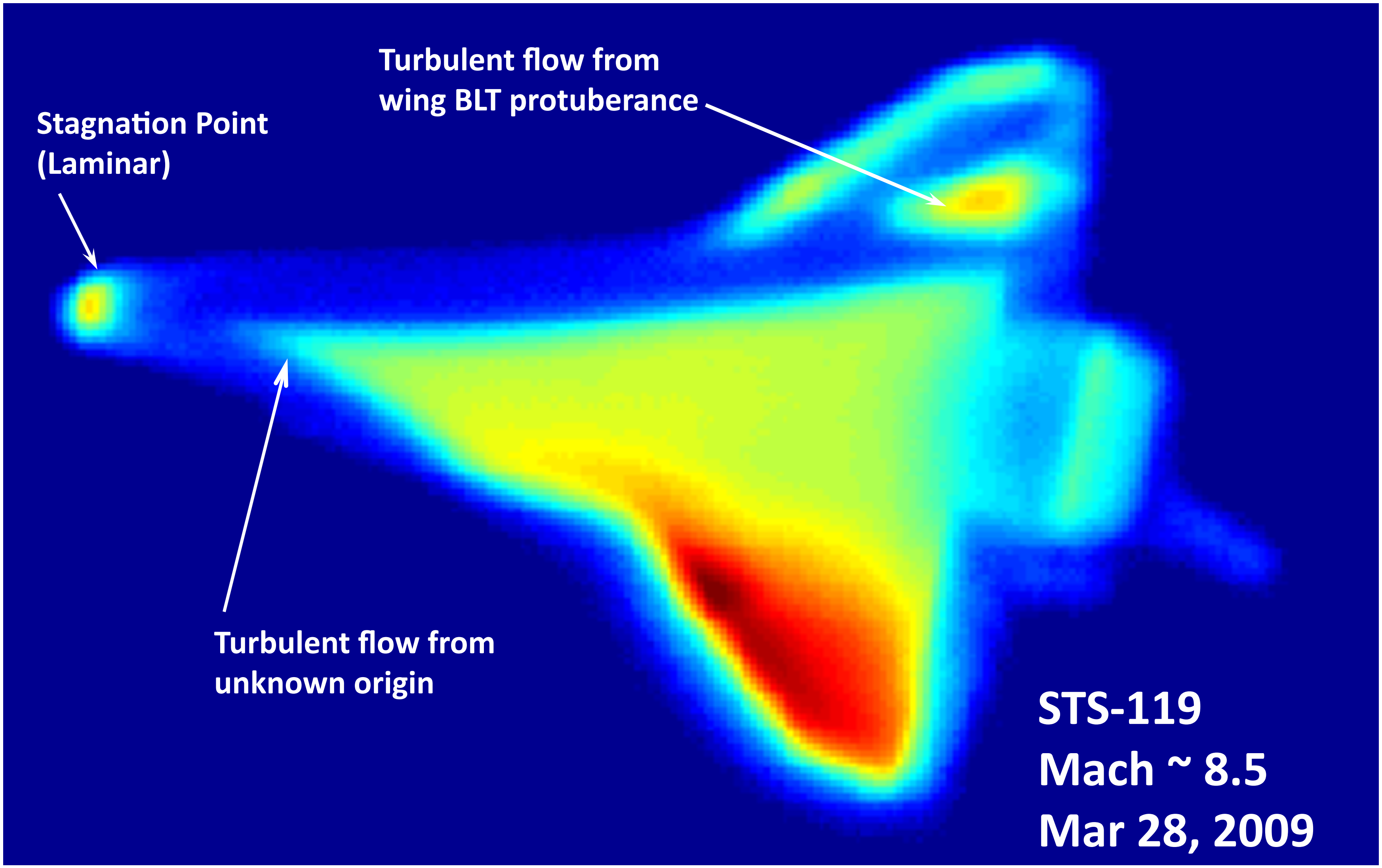
Ref: AIAA 2004-2456

Surface Oilflow
$t = 4900$ s, $Re_D = 7.6\times10^5$



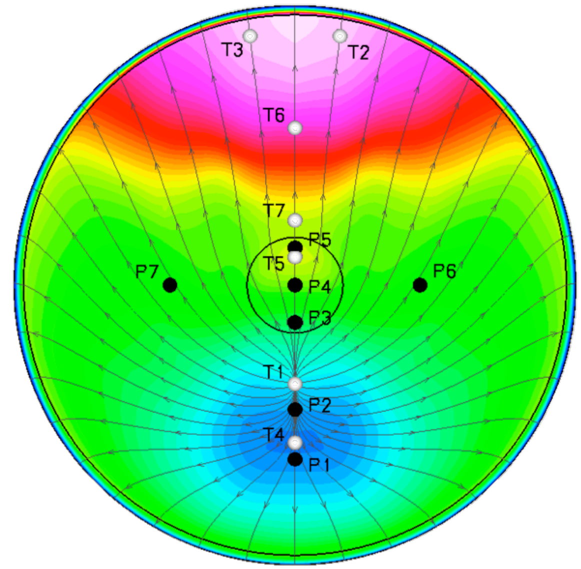
⇒Computations generally agree with flight data to within ±20% uncertainty at 15 of 19 calorimeter locations.

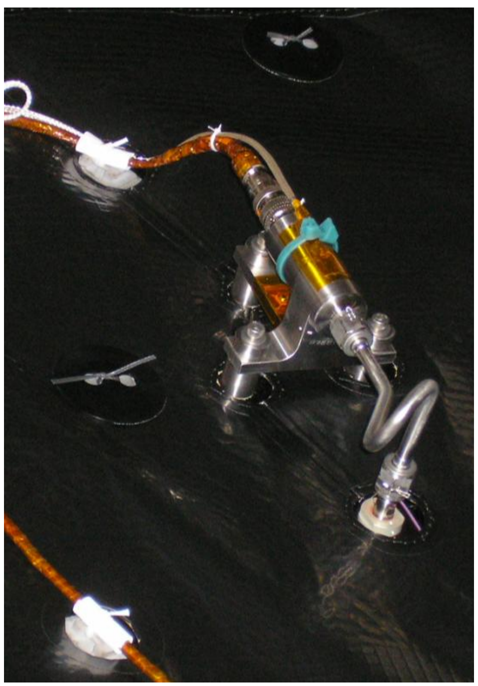
Flight Data: Orbiter Thermal Imagery



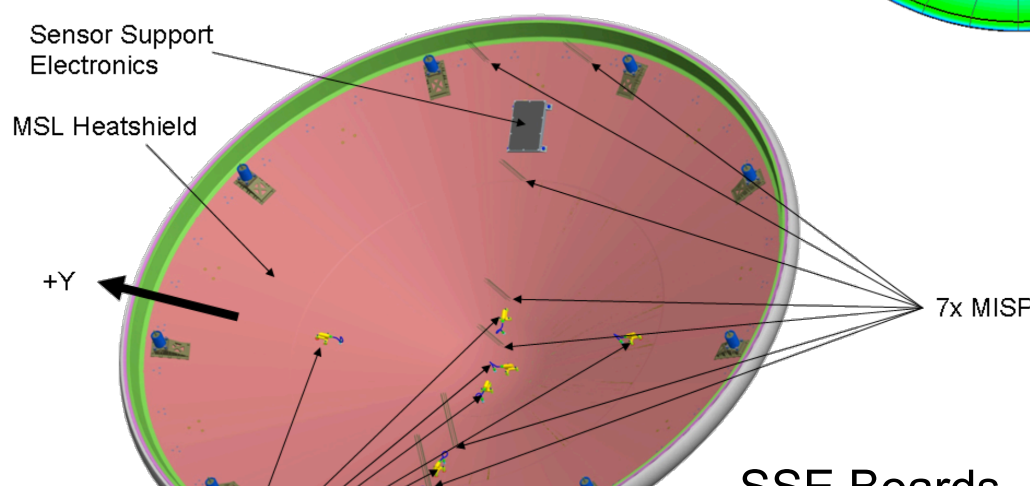
Flight Data: MEDLI

- **MEDLI is an EDL instrumentation suite flying on MSL; launching in November 2011**
- **Will provide invaluable engineering data on aerothermodynamics, aerodynamics, TPS performance, and atmospheric properties during MSL entry**

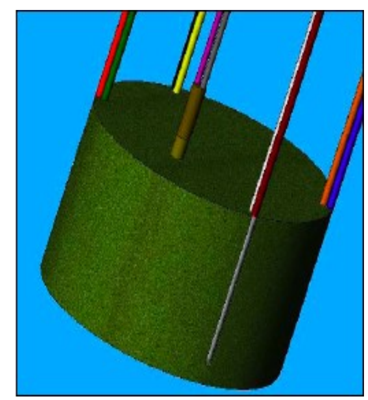




MEADS Assembly



SSE Boards



MISP Plug

Conclusions and Recommendations

- **Three major priorities show up across multiple destinations**
  - Shock layer radiation
  - Turbulent heating and TPS interactions
  - Gas-surface interactions

- **Improvements to aerothermal models for Earth and planetary entries will have a significant payoff in terms of entry risk quantification and reduction as well as system mass**
  - Better understanding of entry risks will enable more informed system trades
  - Aerothermal model improvements may enable a new generation of ambitious science missions
  - Moderate cost, but long lead time. A low-level research initiative now, focused on high priority missions, would ensure that improvements are in place

- **A mix of ground-based testing and theoretical model development, guided by sensitivity/uncertainty analysis, is the best way to advance state-of-the-art to be ready for the next generation of missions**
  - Recommend aerothermal research program, including a mix of NASA and academia, with a mid-term mission focus based on science community feedback